

^3He *experimentum crucis* for Dark Matter puzzles

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Abstract

The leading direct dark matter search experiments: CDMS, Edelweis and DAMA/NaI exhibit different results for different approaches to the problem. This contradiction can reflect a nontrivial and probably a multi-component nature of the cosmological dark matter. WIMPs can possess dominantly a Spin Dependent interaction with nucleons. They can be superheavy or represent atom-like systems of superheavy charged particles. The Dark matter can contain a component, which strongly interacts with the matter. We show that even a moderate size superfluid ^3He detector provides a crucial test for these hypotheses and that its existing laboratory prototype is already of interest for the experimental dark matter search.

1 Introduction

The existence of nonbaryonic dark matter (DM) is one of the cornerstones of modern cosmology. Possible physical candidates for DM particles correspond to different extensions of the Standard Model, describing the known sector of particle physics. Theoretical reasons for such extensions are sufficiently serious to consider these candidates altogether and to expect a multi-component nature of Dark Matter. Recently developed methods of precision cosmology provide the possibility to reveal the dominant form of Dark Matter in astrophysical observations. However, these methods alone are insufficient to explore the problem in all its complexity, so the set of different experimental probes should be developed to distinguish various DM components (including subdominant ones) by their specific effects.

An important step in the exploration of the DM problem was the development of direct searches for Weakly Interacting Massive Particles (WIMP). Underground detectors were created in which effects of nucleus recoil induced by interaction of cosmic WIMP with a nucleus were searched for. As a result of this search DAMA/NaI underground experiment claimed the observation of annual modulation signature [1]. The Si and Ge low temperature experiments with a high level of discrimination did not find the dark matter signals at the corresponding level of probability [2, 3]. The reasons of this discrepancy are now under hot discussion. In particular, this discrepancy can reflect the existence of non-dominant DM component in the form of heavy neutrinos of the 4th generation [4, 5]. A possibility to explain the DAMA/NaI events within the framework of the Standard Model extended to the 4th generation of fermions, described in [4], was recently confronted with the results of CDMS and Edelweiss and it was found that this hypothesis can provide an explanation for all these results. It was also shown in [10] that a wide class of supersymmetric models can also possess this property. It may be a class of DM models of purely Spin Dependent (SD) interaction of WIMPs with nuclei. Another solution can be related with superheavy dark matter particles, which are slowed down in terrestrial matter below a detection threshold of CDMS and Edelweiss. Slowing down assumes strong interaction with matter and the interaction can be so strong that the slowed down particles can not cause any effect above threshold of underground detectors. For such Strongly Interacting Massive Particles (SIMPs) [6] a very small size X-ray detector during only 100 seconds of XQC experiment [7, 8] provided severe constraints. However, the high sensitivity of XQC experiment in tens-eV range is completely lost, when energy release approaches keV range, and there is a gap in experimental sensitivity to energy release in the interval from 1 to 6-10 keV. Moreover, it turns out that the results of XQC experiment are practically insensitive to the existence of such a dark matter candidate, as the recently proposed nuclear-interacting O-helium [9].

Superfluid $^3\text{He-B}$ at ultra-low temperatures is an appealing target material for bolometric particle detection [11, 12, 13], and particularly for the search for non-baryonic Dark Matter. The main arguments in favor of ^3He are its non-zero nuclear magnetic moment (allowing therefore to explore the Spin-Dependent interaction channel) combined to the extremely high sensitivity of superfluid ^3He bolometers and the possibility of efficient neutron background discrimination. It is the purpose of the present paper to specify the class of DM models, for which even moderate size superfluid ^3He bolometers can provide a crucial experimental test.

To minimize the number of free parameters for SD interacting DM we follow the phenomenological framework [1], which provides direct correlation between the results of the DAMA/NaI experiment and the expected signal in superfluid ^3He detectors. Our approach is aimed to study sensitivity of such detectors in a model independent way and is complementary to similar studies for particular models, e.g. for supersymmetric models [10, 14, 15]. We also consider a wider class of dark matter models, involving, in particular, superheavy particles, strongly interacting with matter. The account for nontrivial forms of dark matter, which are not reduced to WIMPs, may be crucial in the resolution of current dark matter puzzles.

2 ^3He response to SD interacting Dark Matter

The results of the analysis of DAMA data for a combination of Spin-Independent (SI) and Spin-Dependent (SD) interaction of WIMPs with matter are given in Fig. 30 of reference [1]. These results are usually presented in terms of the product $\xi\sigma$ of the relative contribution ξ of WIMP density ρ_X into the total local halo density $0.17 < \rho_{loc} < 1.7\text{GeV}/\text{cm}^3$

$$\xi = \frac{\rho_X}{\rho_{loc}} \quad (1)$$

and the cross sections σ of SI and SD interactions.

The values of $\xi\sigma_{SI}$ and $\xi\sigma_{SD}$ differ for SI and SD interactions by 5 orders of magnitude, what provides plausible reasons for testing the purely SD-interacting WIMP nature of DAMA events even in a relatively modest size superfluid ^3He detector.

2.1 Qualitative estimation

We first give rough estimation of the expected number of events in a detector containing N_m moles of superfluid ^3He .

Let $n = \xi \frac{\rho_{loc}}{m_X}$ be the local number density of WIMPs with mass m_X and galactic averaged velocity v ($v \sim 300$ km/s). For the cross section σ_{SD} the number of events N_{ev} expected in the detector during the period $T \sim 1$ year of its operation is given by

$$N_{ev} = n \sigma_{SD} v T N_A N_m, \quad (2)$$

where $N_A = 6 \cdot 10^{23} \text{ mole}^{-1}$ is the Avogadro number.

We can estimate the minimal number of events, corresponding to the lower limits on $\xi \sigma_{SD}$ in [1]. This minimal estimation corresponds to maximal values of the astrophysical parameter $\rho_{loc} = 1.7 \text{ GeV/cm}^3$, so that $n = 3.4 \cdot 10^{-2} \cdot \xi \cdot \left(\frac{50 \text{ GeV}}{m_X}\right) \text{ cm}^{-3}$.

For this minimal estimation one obtains from Eq.(2)

$$N_{ev} = 18 \frac{(\xi \sigma_{SD})_{min}}{1 \text{ pb}} N_m \left(\frac{v}{300 \text{ km/s}}\right) \left(\frac{T}{1 \text{ yr}}\right) \left(\frac{50 \text{ GeV}}{m_X}\right).$$

Since in the whole range of SD-interacting WIMP parameters, reproducing the DAMA result, the value of $(\xi \sigma_{SD})_{min} > 10^{-2} \text{ pb}$, $v > 100 \text{ km/s}$, $m_X < 110 \text{ GeV}$, one finds that a detector containing $N_m \geq 30$ moles of superfluid ^3He can cover all the possible range of these parameters during one year of operation. It would provide a complete experimental test for the SD-interacting WIMP interpretation of the DAMA event. However, this general optimistic estimation should be taken with caution in view of the theoretical uncertainty in the possible parameters and nature of the SD interaction.

2.2 Phenomenology of SD interacting WIMPs

In the non-relativistic limit, which is appropriate for WIMPs in the Galaxy, the variety of possible forms of WIMP-nucleus interaction is reduced to two cases, namely, to a spin-spin interaction and to a scalar one. Fundamental constants of WIMP interaction with nucleon constituents, being specified by each concrete particle model, determine the effective coupling of WIMPs to nucleons, which, in turn, defines constants of WIMP-nucleus interaction (for a more detailed review see [16, 17, 18]). The essential difference between spin-spin and scalar interactions is in the following. In the scalar case, the WIMP-nucleus interaction amplitude (A_{XA}) is given by the WIMP-nucleon ($A_{Xp,n}$) amplitude, multiplied by the number of respective nucleons, while in the spin-spin case A_{XA} is proportional to the nucleon spin averaged over the nucleus state $\langle S_{p,n} \rangle$, which for heavy non-zero spin nuclei is, as a rule, even smaller than that for a single nucleon ($S_p = S_n = 1/2$). It leads to a loss of advantage in using heavy target-nuclei in the exploration of WIMPs with spin dependent interaction.

Let us denote, according to [1, 16], a_p and a_n the coupling constants of WIMP SD-interaction with proton and neutron, respectively. Then the cross section of SD interaction between WIMP and a nucleus with spin J can be represented as [1]

$$\sigma_{SD} = \left(\frac{\mu_{XA}}{\mu_{Xp}}\right)^2 \frac{4}{3} \frac{J+1}{J} \sigma_{SD}^{(np)} (\langle S_p \rangle \cos \theta + \langle S_n \rangle \sin \theta)^2 G_{SD}. \quad (3)$$

Here, following [1], a parameter $\theta = \arctg \frac{a_n}{a_p}$ is introduced to characterize the relative contribution to WIMP-nucleus interaction from WIMP-proton and WIMP-neutron couplings. In (3) μ_{Xp} and μ_{XA} are the reduced masses of WIMP (m_X) and proton (nucleon) (m_p) and nucleus (m_A),

$$\sigma_{SD}^{(np)} = \frac{32}{\pi} \frac{3}{4} G_F^2 \mu_{Xp} (a_p^2 + a_n^2) \quad (4)$$

being denoted in [1] as σ_{SD} ,

$$G_{SD} = \frac{1}{E_{R \max}} \int_0^{E_{R \max}} F_{SD}^2(E_R) dE_R \quad (5)$$

takes into account effects of the finite size of the nucleus (a loss of coherence). The effect of the finite size of nucleus is conveniently parametrized by dimensionless $y = \left(\frac{|\vec{q}|b}{2}\right)^2 = \frac{m_A E_R b^2}{2}$ with \vec{q} being transferred momentum and $b = 1 \text{ fm } A^{1/6}$ (or more precisely [19] $b = \sqrt{\frac{41.467}{45A^{-1/3} - 25A^{-2/3}}} \text{ fm}$). For $y \ll 1$, $G_{SD} = 1$. The representation of σ_{SD} by Eq.(3) implies normalization of the form-factor F_{SD} on unity at zero transferred energy E_R

$$F_{SD}^2 = \frac{S(E_R)}{S(0)}. \quad (6)$$

The function $S(E_R)$ is conventionally divided in isovector (S_{11}), isoscalar (S_{00}) and interference (S_{01}) parts and has the form

$$S(y) = (a_p + a_n)^2 S_{00}(y) + (a_p - a_n)^2 S_{11}(y) + (a_p^2 - a_n^2) S_{01}(y). \quad (7)$$

Since a_p and a_n directly enter this expression, S depends on the type of WIMP. The larger is the dimensionless argument y , the stronger is the suppression due to finite nucleus size. F_{SD} , being defined in the form of Eq.(6), depends on the WIMP type ($a_{p,n}$) only through θ (which in first approximation can be neglected for ^{23}Na and ^{127}I , used in DAMA/NaI setup [20]). It makes the value $\sigma_{SD}^{(np)}$ inferred from DAMA measurements (see Eq.(3)) less WIMP model-dependent at fixed θ .

Eventually one notes, that Eq.(3) represents SD WIMP-nucleus cross-section through three WIMP-type dependent parameters: $\sigma_{SD}^{(np)}(a_p, a_n)$, $\theta(a_p/a_n)$ and m_X . The values $\langle S_{p,n} \rangle$ and functions $S_{ij}(y)$ are defined by a particular nuclear model and suffer with considerable uncertainties [1, 16, 19].

2.3 The expected event rates in ^3He

There is an important difference between the nucleus ^3He and nuclei ^{23}Na and ^{127}I , used in DAMA/NaI set-up. ^3He has an unpaired neutron and is an even-odd nucleus (in terms of numbers of its protons and neutrons). As a consequence, the spin of this nucleus is determined mainly by the neutron¹ $\langle S_p \rangle \approx 0$, $\langle S_n \rangle \neq 0$, while ^{23}Na and ^{127}I are odd-even and for them $\langle S_p \rangle \neq 0$, $\langle S_n \rangle \approx 0$. Deviation of $\langle S_p \rangle$ from zero for even-proton nuclei (and analogously for even-neutron) is determined by the details of nuclear model [19]. But for the "simply" composed ^3He nucleus ($J = 1/2$) it will be quite accurate to use the single particle (or also odd group) shell model of nucleus which gives here $\langle S_p \rangle = 0$, $\langle S_n \rangle = 1/2$ [16].

The effect of finite size of ^3He is insignificant. Estimation of the maximal magnitude of y shows it. The maximal transferred (recoil) momentum for an incident WIMP with velocity v is $|\vec{q}_{\max}| = 2\mu_{XA}v$. Taking into account that $\mu_{XA} < \min\{m_A, m_X\} \leq m_A$, $v < 700 \text{ km/s}$ one obtains for ^3He $y < 1.6 \cdot 10^{-3} \ll 1$. So we will reasonably assume $G_{SD} = 1$.

WIMP- ^3He SD cross section can be written as

$$\sigma_{SD} = \left(\frac{\mu_{XA}}{\mu_{Xp}}\right)^2 \sigma_{SD}^{(np)} \sin^2 \theta. \quad (8)$$

For a given σ_{SD} the event rate in a ^3He setup will be

$$\text{Rate} = \frac{\xi \rho_{loc}}{m_X} \sigma_{SD} \bar{v} N_A N_m, \quad (9)$$

where \bar{v} is the mean WIMP velocity, which exceeds the threshold value, corresponding to the minimal energy release ($E_{Rmin} = 1 \text{ keV}$) in ^3He setup. Possible dependence of $\xi \sigma_{SD}^{(np)}$ on m_X has been deduced from the analysis of positive results of DAMA measurements for different θ , taking into account uncertainties in ρ_{loc} and WIMP velocity distribution (i.e. \bar{v}). As a first approximation in the estimation of the expected rate on the basis of DAMA data, we will fix $\rho_{loc} = 0.3 \text{ GeV/cm}^3$, $\bar{v} = 250 \text{ km/s}$ for all plots of DAMA (all boundaries enclosing an allowable region). This simplification prevents double account of uncertainties in ρ_{loc} and \bar{v} (first one in $\xi \sigma_{SD}^{(np)}$ and second one in Rate).

¹In principle, this statement does not mean that $\langle S_n \rangle = J$, because nucleons' orbital momentum in most cases essentially contributes into J too. However, this is not the case for ^3He .

Expected rates per 1 g of superfluid ^3He , obtained on the basis of DAMA data, are shown on Fig.1 for two cases: $\theta = \pi/2$ (Fig.30c of [1]) and $\theta = 2.435$ (Fig.30d of [1]). The case $\theta = \pi/2$ corresponds to WIMP coupling to neutrons only ($a_n \neq 0$, $a_p = 0$), what is the most preferable case for the ^3He setup. The case $\theta = 2.435$ ($a_n/a_p = -0.85$) takes place for the neutralino with purely Z^0 -boson mediated interaction with nuclei. The case of $\theta = 0$ (WIMPs interact with only protons) is virtually insensitive for a ^3He setup. Note that in a ^3He setup containing 100 g of superfluid ^3He the rate of event should exceed one events per month.

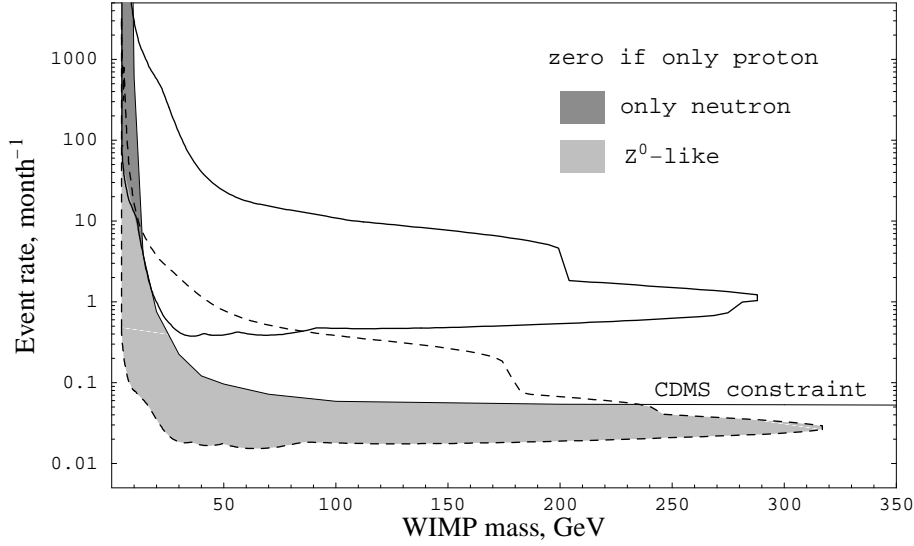


Figure 1: Expected signal in 1 g of superfluid He-3 detector for the interpretation of DAMA/NaI results in terms of purely Spin Dependent interaction. Two regions, enclosed by solid and dash lines, correspond to expected event rates for WIMP-nucleon coupling parameters $\theta = \pi/2$ and $\theta = 2.435$ respectively (see text). CDMS constraint on WIMP-neutron SD cross section is taken into account (thin solid line); it reduces the expected rate region based on DAMA/NaI as shown by shading.

Experiments CDMS and Edelweiss are virtually insensitive to WIMP-proton SD interaction (a_p) too. Natural Ge, used in them, contains mainly spinless isotopes and one odd-neutron isotope ^{73}Ge . Therefore CDMS and Edelweiss are sensitive to WIMP-neutron SD interaction (a_n) but suppressed in proportion to the small abundance fraction of ^{73}Ge in ^{nat}Ge ($\sim 8\%$) [2] (In the detector of CDMS II experiment, being under run, Si is also used [21]). However, the sensitivity of DAMA/NaI to a_n is suppressed too, because for (even-neutron) ^{127}I ($\langle S_n \rangle / \langle S_p \rangle \rangle^2 \sim 1/30$ (for ^{23}Na it is even smaller). It makes results of CDMS and Edelweiss important for the exploration of the allowed parameter range for SD interacting WIMPs [18, 23]. Some information about this range can be provided by other experiments. Zeplin [22] and DAMA/Xe, based on Xe containing odd-neutron isotopes, are sensitive to a_n , NAIAD(NaI) [25] and CRESST-I(Al) [24] are sensitive to a_p , while SIMPLE(C_2ClF_5) [23] is sensitive to a_p and less sensitive to a_n . In particular, CDMS data might impose strong constraints on WIMP-neutron SD cross section $\sigma_{Xn}(a_p = 0)$ [26, 2]. For illustration, we took into account the constraint [2] in estimation of the expected event rate in ^3He set up (see Fig.1). The value σ_{Xn} , limited by CDMS at $a_p = 0$ ($\theta = \pi/2$), in terms of introduced notation is $\sigma_{Xn} = \sigma_{SD}^{(np)} \sin^2 \theta$, entering directly the event rate for ^3He set up. In our estimation we treated the limit on $\sigma_{Xn}(\theta = \pi/2)$ as the limit on this magnitude at any θ . Such treatment neglects the contribution of the WIMP-proton interaction which is important for target nuclei of CDMS at small θ and neglects soft θ -dependence of G_{SD} [20].

Unfortunately, due to the lack of complete experimental details, it is not possible for us to reanalyze all existing experiments to infer what can be expected using ^3He . We therefore concentrate on the DAMA/NaI results, in particular on the nature of the positive signals recorded by their experiment.

However it is important to note that the low WIMP mass range, where the positive signal of DAMA/NaI is near its energy threshold, is almost inaccessible for probing by other experiments, whereas it can be fully covered by the He-3 experiment even for an extremely small contribution due to a_n .

3 Multi-component Dark Matter and He-3 detector

There are a few severely constrained possibilities [18] to explain the discrepancy in the results of underground experiments.

For instance, DM particles can be so slow that they are inaccessible for detection by CDMS while accessible for DAMA. These particles can have a non-standard distribution in the neighborhood of the Solar system, being slow with respect to it initially. In the latter case, annual modulations remain, but the effect goes below the energy threshold of other detectors.

One can suppose that a DM particle possesses such a strong interaction that it loses its energy going to the detector through matter (atmosphere and rock) to be able to produce an effect inside the detector of DAMA/NaI just in a given range, and not able to do that in CDMS and Edelweiss, being below their thresholds. For an estimation we assume that $m_X \gg m_A$ for all nuclei constituting the detectors (note, that m_X relates here to SIMP - Strongly Interacting Massive Particle). In this case, the recoil energy of the nucleus lies in the range $0 \dots 2m_A v^2 = 4 \frac{m_A}{m_X} E$, where v and E are the SIMP initial velocity and energy respectively, and the energy loss of SIMP in each similar collision is $2m_A/m_X E$.

One can pick out two conditions for such SIMPs to be viable candidates accounting for the results of underground experiments. First, SIMPs must lose sufficient energy before reaching the detectors. Second, the recoil energy spectrum in DAMA must be ranged below 10 keV. It gives the range of possible masses and cross sections for SIMPs, which will be accessible to a superfluid ^3He detector.

In the multi-component dark matter framework the coexistence of different components implies experimental means of their discrimination. In such general context various types of DM detectors can be complementary and sensitive to different DM components. In particular, taking into account possible non-WIMP interpretation of DAMA/NaI data in terms of light scalar bosons [27] or various multi-component scenarios, such as [28], one should accept a more general approach and investigate the efficiency of a He3 set-up to various DM candidates without normalization on underground experiment data. We illustrate this approach by a successive discussion of possible test for composite dark matter models.

3.1 Composite dark matter and its species

The recently proposed "sinister" $SU(3)_c \times SU(2) \times SU(2)' \times U(1)$ gauge model [29] offers an interesting realization for superheavy WIMPs. It involves three heavy generations of tera-fermions, which are related with ordinary light fermions (quarks and leptons) by CP' transformation linking light fermions to charge conjugates of their heavy partners and vice versa. CP' symmetry breaking makes tera-fermions much heavier than their light partners. Tera-fermion mass pattern is the same as for light generations, but all the masses are multiplied by the same factor $S > 2 \cdot 10^5$. Strict conservation of $F = (B - L) - (B' - L')$ prevents mixing of charged tera-fermions with light quarks and leptons. Tera-fermions are sterile relative to $SU(2)$ electroweak interaction: they do not interact with W , Z and Higgs bosons and thus do not contribute to standard model parameters. That is why precise measurement of these parameters puts no constraints on properties of tera-particles. In such realization, the new heavy neutrinos (N_i) acquire large masses and their mixing with light neutrinos ν provides a "see-saw" mechanism of light neutrino Dirac mass generation. Therefore in a Sinister model the heavy neutrino is unstable. On the contrary, in this scheme E is the lightest heavy fermion and it is absolutely stable.

In the "Sinister" scenario very heavy quarks Q (or antiquarks \bar{Q}) can form bound states with other heavy quarks (or antiquarks) due to their Coulomb-like QCD attraction, and the binding energy of these states may

substantially exceed the binding energy of QCD confinement. Then (QQq) and (QQQ) baryons must exist. In the model [29] the properties of heavy generation fermions are fixed by their discrete CP' symmetry with light fermions. According to this model a heavy quark U with mass $m_U = S \cdot m_u = S \cdot 3.5 MeV$ and heavy electron E ($m_E = S \cdot m_e = S \cdot 0.5 MeV$) are stable and can form a neutral and strongly bound $(UUUEE)$ "atom" with (UUU) hadron (spin 3/2) as nucleus and two E s as "electrons". The tera gas of such "atoms" can be a candidate for dark matter.

There is an uncertainty in the estimation of cross section of tera-helium interaction with nuclei. Hadronic interaction of (UUU) with ordinary nucleons is strongly suppressed, due to a very small size of this "baryon", which can not be resolved by gluons from ordinary baryons. The minimal estimation comes from the interaction of the (UUU) magnetic moment with the charge of nucleus. The cross section of spin 3/2 particle with magnetic moment on a point-like fermion of charge eZ in the non-relativistic limit is given by

$$\sigma = \frac{5}{36\pi} \mu^2 e^2 Z^2 (1 + \log \left(\frac{2MV^2}{E_{1min} - M} \right)). \quad (10)$$

Here μ is the magnetic moment, M the mass of nucleus, V the speed of dark matter particles in units of c , E_{1min} the detector threshold for recoil nuclei. The cross section can be estimated as

$$\sigma = \frac{5}{36\pi} \mu^2 e^2 Z^2 \sim Z^2 (g/2)^2 2.4 \cdot 10^{-34} \left(\frac{m_p}{m_X} \right)^2 cm^2, \quad (11)$$

where g is the Lande factor ($g = 4$ for spin 3/2), m_X the mass of terahelium particle ($m_X > 2.3 TeV$), m_p the proton mass.

The problem of such scenario is inevitable presence of "products of incomplete combustion" and the necessity to decrease their abundance. Indeed in analogy to D, 3He and Li relics that are the intermediate catalyzers of 4He formation in Standard Big Bang Nucleosynthesis (SBBN) and are important cosmological tracers of this process, the tera-lepton and tera-hadron relics from intermediate stages of a multi-step process of towards a final $(UUUEE)$ formation must survive with high abundance of *visible* relics in the present Universe. To avoid this trouble an original idea of (Ep) catalysis was proposed in [29]: as soon as the temperature falls down below $T \sim I_{Ep}/25 \sim 1 keV$ neutral (Ep) atom with "ionization potential" $I_{Ep} = \alpha^2 m_p/2 = 25 keV$ can be formed. The hope was [29] that this "atom" must catalyze additional effective binding of various tera-particle species and to reduce their abundance below the experimental upper limits.

Unfortunately, as it was shown in [30], this fascinating picture of Sinister Universe can not be realized. Tracing in more details cosmological evolution of tera-matter and strictly following the conjecture of [29], the troubles of this approach were revealed and gracious exit from them for any model assuming -1 charge component of composite atom-like dark matter was found impossible.

The grave problem is that ordinary 4He formed in Standard Big Bang Nucleosynthesis binds at $T \sim 15 keV$ virtually all the free E^- into positively charged $(^4HeE^-)^+$ "ion", which puts a Coulomb barrier for any successive E^-E^+ annihilation or any effective EU binding. It happens *before* the (Ep) atom can be formed and (Ep) atoms can not be formed, since all the free E are already imprisoned by a 4He cage. It removes the hope [29] on (Ep) atomic catalysis as *panacea* from unwanted tera-particle species. The huge frozen abundance of tera-leptons in hybrid tera-positronium (eE^+) and hybrid hydrogen-like tera-helium atom (4HeEe) and in other complex anomalous isotopes can not be removed [30].

In spite of this grave problem the idea of Glashow's Sinister Universe was very inspiring, and composite dark matter scenarios, avoiding this trouble, were developed.

The AC-model [31] appeared as realistic elementary particle model, based on the specific approach of [32] to unify general relativity, quantum mechanics and gauge symmetry.

This realization naturally embeds the Standard model, both reproducing its gauge symmetry and Higgs mechanism, but to be realistic, it should go beyond the standard model and offer candidates for dark matter. Postulates of noncommutative geometry put severe constraints on the gauge symmetry group, excluding in this approach, which can be considered as alternative to superstring phenomenology, supersymmetric and GUT

extensions. The AC-model [31] extends the fermion content of the Standard model by two heavy particles with opposite electromagnetic and Z-boson charges. Having no other gauge charges of the Standard model, these particles (AC-fermions) behave as heavy stable leptons with charges $-2e$ and $+2e$, called A and C , respectively. AC-fermions are sterile relative to $SU(2)$ electro-weak interaction, and do not contribute to the standard model parameters. In the absence of AC-fermion mixing with light fermions, AC-fermions can be absolutely stable. The lower limit for the mass of AC-fermions follows from absence of new charged leptons in LEP. It was assumed in [33, 34] that $m_A = m_C = m = 100S_2$ GeV with free parameter $S_2 \geq 1$.

Primordial excessive negatively charged A^{--} and positively charged C^{++} form a neutral most probable and stable (while being evanescent) (AC) "atom", the AC-gas of such "atoms" being a candidate for dark matter [31, 33, 34, 36].

However, similar to the sinister Universe AC-lepton relics from intermediate stages of a multi-step process towards a final (AC) atom formation must survive with high abundance of *visible* relics in the present Universe. In spite of the assumed excess of particles (A^{--} and C^{++}) abundance of frozen out antiparticles (\bar{A}^{++} and \bar{C}^{--}) is not negligible, as well as significant fraction of A^{--} and C^{++} remains unbound, when AC recombination takes place and most of AC-leptons form (AC) atoms. This problem of unavoidable over-abundance of by-products of "incomplete combustion" is avoided in AC-model owing to the double negative charge of A^{--} [33, 34, 36]. As soon as ${}^4\text{He}$ is formed in Big Bang nucleosynthesis it captures all the free negatively charged heavy particles. Instead of positively charged ions, created in the Sinister Universe, the primordial component of free anion-like AC-leptons A^{--} are mostly trapped in the first three minutes into a puzzling neutral O-helium state (${}^4\text{He}^{++}A^{--}$), with nuclear interaction cross section, which provides anywhere eventual later (AC) binding. As soon as O-helium forms, it catalyzes in the first three minutes effective binding in (AC) atoms and complete annihilation of antiparticles. Products of annihilation cause undesirable effect neither in CMB spectrum, nor in light element abundances. O-helium, this surprising α -particle with screened Coulomb barrier, can influence the chemical evolution of ordinary matter, but might not result in over-production of anomalous isotopes [33, 34, 36].

At small energy transfer $\Delta E \ll m$ cross section for interaction of AC-atoms with matter is suppressed by the factor $\sim Z^2(\Delta E/m)^2$, being for scattering on nuclei with charge Z and atomic weight A of the order of $\sigma_{ACZ} \sim Z^2/\pi(\Delta E/m)^2\sigma_{AC} \sim Z^2A^210^{-43}\text{cm}^2/S_2^2$. Here we take $\Delta E \sim 2Am_pv^2$ and $v/c \sim 10^{-3}$ and find that even for heavy nuclei with $Z \sim 100$ and $A \sim 200$ this cross section does not exceed $4 \cdot 10^{-35}\text{cm}^2/S_2^2$. It proves WIMP-like behavior of AC-atoms in the ordinary matter.

However, composite atom-like WIMPs, being the challenge for underground DM search (in particular with the use of ${}^3\text{He}$ detector), are inevitably accompanied by a nuclear interacting O-helium component. It is even possible that this component is the dominant form of the modern dark matter [9].

3.2 Possible effect of O-helium in ${}^3\text{He}$

The terrestrial matter is opaque for O-helium and stores all its in-falling flux. Therefore, the first evident consequence of the proposed scenario is the inevitable presence of O-helium in Earth. If its interaction with matter is dominantly quasi-elastic, the O-helium flux moves downward to the center of Earth. If O-helium regeneration is not effective and Δ remains bound with heavy nucleus Z , anomalous isotope of $Z - 2$ element appears. This is the serious problem for the considered model.

O-helium density can be expressed through the local dark matter density $\rho_o = \xi_{OHe} \cdot \rho_{loc}$ ($\xi_{OHe} \leq 1$), saturating it at $\xi_{OHe} = 1$. Even at $\xi_{OHe} = 1$ O-helium gives rise to less than 0.1 [9, 35, 36] of expected background events in XQC experiment [7], thus avoiding for all $\xi_{OHe} \leq 1$ severe constraints on Strongly Interacting Massive particles SIMPs obtained in [37] from the results of this experiment. In underground detectors O-helium species are slowed down to thermal energies far below the threshold for direct dark matter detection.

Therefore a special strategy in the search for this form of dark matter is needed.

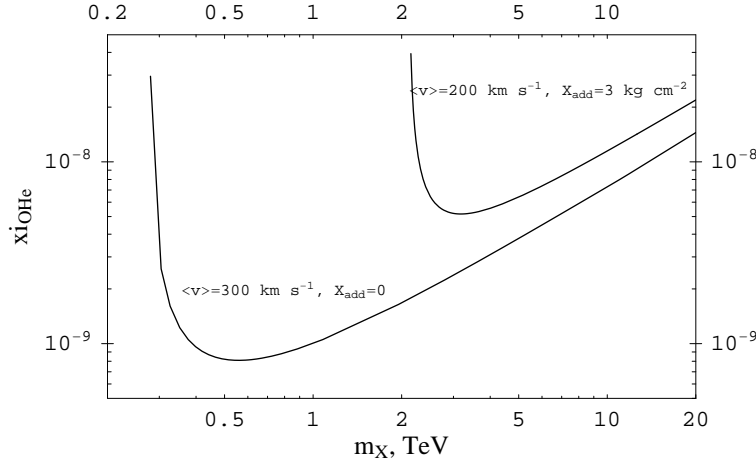


Figure 2: The levels of sensitivity of 1 g of ^3He detector (corresponding to one event per month of operation) to the relative abundance ξ_{OHe} of cosmic OHe in vicinity of Earth versus O-helium mass m_X . The upper and lower curves correspond to the maximal and minimal estimations of the effect of OHe slowing down. The upper curve also takes into account possible effect of slowing down of OHe flux due to collisions with the matter of the roof, walls and ceilings of laboratory building.

An interesting possibility appears with the development of superfluid ^3He detectors [38]. Due to the high sensitivity to energy release above ($E_{th} = 1\text{ keV}$), the operation of a few gram prototype can put severe constraints on a wide range of ξ_{OHe} and O-helium mass m_X . We can illustrate it by the following simple estimation. Indeed, the initial kinetic energy $E \sim \frac{m_X(300\text{ km/s}/c)^2}{2}$ of cosmic O-helium of mass m_X , falling downward to the center of the Earth, decreases due to collisions with matter nuclei with the rate per the unit length

$$dE/dX = -\Delta E/X_{mat}. \quad (12)$$

Here $\Delta E = \frac{2m_A}{m_X}E$ is the averaged energy loss in a collision with atomic nucleus with the mass m_A . The mean mass of nuclei in atmosphere can be taken as $m_A \approx 15$ and the nuclear collision length in it is $X_{mat} \approx 60\text{ g/cm}^2$. We can also take into account additional energy losses due to collisions with atomic nuclei of matter in roof, ceilings and walls of laboratory building. To be registered by a He-3 detector, the kinetic energy of slowed down O-helium, which is determined by Eq.(12) and given by

$$E_{det} = E \exp\left(-\frac{2m_A}{m_X} \frac{X(\theta)}{X_{mat}}\right), \quad (13)$$

should be sufficiently high to produce a signal in the detector above the threshold E_{th} . The length $X(\theta)$ travelled by a cosmic O-helium before reaching the detector depends on its initial direction and includes the thickness of the atmosphere $X_{atm}(\theta)$ and the additional thickness X_{add} of the laboratory building where the detector operates. The condition that the energy transfer to ^3He exceeds the detection threshold $E_{Rmax} = 4m_{^3\text{He}}E_{det}/m_X > E_{th} = 1\text{ keV}$ fixes possible directions (solid angles) for incoming O-helium flux to be detected in the He-3 detector. The level of sensitivity of 1 g of superfluid ^3He to the local relative density of O-helium with mass m_X is shown on the figure 2. This level is roughly estimated as corresponding to one event registered during one month of detector operation. The simulation of O-helium events in the detector and the analysis of their detection efficiency are of special interest and will be considered elsewhere.

These estimations demonstrate that the analysis of the data from the existing detector prototype can provide a sensitive test of composite dark matter models in a wide range of their parameters. O-helium with smaller masses can escape this test due to effective slowing down below the detection threshold. However, at these masses experimental search for charged constituents of O-helium (A -leptons of AC-model or stable quarks of 4th generation of model [9]) is possible in the nearest future at accelerators [36].

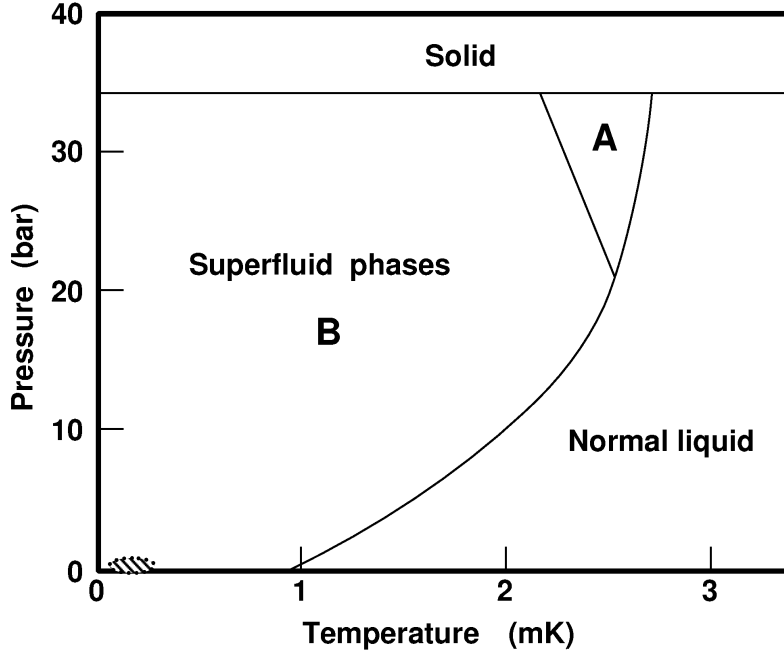


Figure 3: ^3He phase diagram in the milliKelvin range and for 0 magnetic field. Above 34 bar ^3He is solid at these temperatures. The “normal” Fermi liquid ^3He has a superfluid phase transition at a temperature T_c varying from 0.93 to 2.49 mK between vapor pressure and melting pressure. The complex order parameter associated to the phase transition allows the existence of various superfluid phases with different broken symmetries, two of which are represented here (see text for details). The working point of the detector is within the shaded area near the origin.

4 Superfluid He-3 test for Dark Matter

4.1 Superfluid ^3He at ultra-low temperatures

Many collaborations have developed promising detectors to search for non-baryonic dark matter. These detectors have reached sufficient sensitivity to probe the existence of various dark matter candidates, including even sparse sub-dominant components. In particular, such sensitivity allows to test some regions of the SUSY parameter space [10] or properties of 4th family of quarks and leptons [4].

Direct detection experiments present common problems such as neutron interaction background and radioactivity contamination from both the sensitive medium and the surrounding materials. Substantial experimental research has been devoted to the development of different types of detectors, in order to optimize the sensitivity while keeping to a minimum the undesirable effects. Based on early experimental works, a superfluid ^3He detector for direct detection of non-baryonic dark matter has been proposed [11, 12]. The first experimental tests of a ^3He detector by neutrons and γ -rays have been done in Lancaster and Grenoble [13, 39, 40].

^3He is a quantum fluid obeying Fermi statistics, and it remains liquid down to the absolute zero of temperature. At about 1~2.5 mK (depending on the pressure), liquid ^3He displays a second order phase transition to its superfluid A- and B-phases, as shown in figure 3. The superfluid A phase has an anisotropic gap structure and an order parameter mixing magnetic and flow properties, while the B phase is characterized by an isotropic gap $\Delta = 1.76 k_B T_c$ well described at 0 pressure by the weak coupling BCS theory [41]. Experimental temperatures as low as 100 μK are achieved by adiabatic nuclear demagnetization of a copper stage, which then cools down the liquid ^3He [42]. At these temperatures far below the transition temperature T_c , the superfluid is in its isotropic

B-phase and the density of thermal excitations (quasiparticles) n decreases exponentially with temperature

$$n = \int g(E)dE = \frac{N_A}{V} \sqrt{2\pi \frac{\Delta}{k_B T}} \exp(-\Delta/k_B T), \quad (14)$$

where $g(E)$ is the density of states, N_A is Avogadro's number and V the molar volume of the fluid. This density is so low that the liquid can be represented as a renormalized quantum vacuum carrying a dilute quasiparticle gas. In the range of 100 to 200 μ K, the heat capacity of the superfluid is dominated by the ballistic quasiparticle gas and reduces to

$$C = C_0 \left(\frac{T_c}{T} \right)^{3/2} \exp(-\Delta/k_B T), \quad (15)$$

with $C_0 \approx 2.1 \text{ mJ K}^{-1} \text{cm}^{-3}$.

A direct and rather rapid method of thermometry of the superfluid is achieved by measuring the density of thermal excitations (quasiparticles) using Vibrating Wire Resonators (VWRs) [43]. A VWR is a fine superconducting wire bent into semi-circular shape and oscillating perpendicularly to its plane. The excitation and the read-out of the VWR are obtained by electrical (a.c. current) means.

The dynamics of the VWR can be conveniently described by a damped harmonic oscillator model. The damping of the VWR is dominated by the friction with the quasiparticle gas of the surrounding superfluid [44]. The damping of the oscillator and thus the resonance line-width at half-height W are proportional to $\int v_g g(E)dE$, where v_g is the quasiparticle group velocity, and may be expressed as a function of temperature

$$W(T) = W_0 \exp(-\Delta/k_B T). \quad (16)$$

W exhibits therefore an extremely steep temperature dependence around 100 μ K. The continuous measurement of W allows to access temperature with response times $\tau_{wire} = 1/\pi W < 1 \text{ s}$ for typical values of W of the order of 1 Hz. The VWR being immersed in the target medium provides a sensitive and direct measurement of the temperature.

4.2 ^3He as a target material for Dark Matter search

For the bolometric particle detection we use copper cells of typical dimensions about 5 mm, filled with superfluid ^3He which is in weak thermal contact with the outer bath through a small orifice [13, 39, 45]. The interaction of a particle with the ^3He in the cell releases energy which results in an increase of temperature, and thus n . The time constants of internal equilibrium of the quasi-particle gas are small ($< 1 \text{ ms}$), while the time constant for thermal relaxation of quasiparticles through the orifice after a heating event is tuned to be $\tau_{cell} \approx 5 \text{ s}$. The heat leak through the container walls can be neglected because of the huge thermal resistance (Kapitza resistance) of solid-liquid interfaces at very low temperatures. Each bolometric cell contains a least one VWR-thermometer which allows to follow the rapid variations of the temperature.

Bolometric calibration of the detector cells is achieved by an extra VWR present in the cell that can produce a short mechanical pulse at its resonant frequency and thus deposit a well-controlled amount of energy (heat) to the liquid through mechanical friction [39, 45].

While the use of ^3He imposes challenging technological - namely cryogenical - constraints, this material has nevertheless extremely appealing features for Dark Matter detection :

- The ^3He nucleus having a non-zero magnetic moment, a ^3He detector will be mainly sensitive to the axial interaction [10], making this device complementary to existing ones, mainly sensitive to the scalar interaction. The axial interaction is largely dominant in most of the SUSY region associated with a substantial elastic cross-section.

- The purity of bulk liquid ^3He at 100 μ K is virtually absolute. Nothing can dissolve in ^3He at these temperatures; no magnetic impurities.

- ^3He presents the rather unique feature of a high neutron capture cross-section. The nuclear capture reaction



leads to a large energy release of 764 keV. Neutron contamination has thus a clear signature [13, 40], well discriminated from a WIMP signal.

- The discrimination of elastic neutron scattering can be done by well known method of multicell detectors, as it was discussed for superfluid ^3He case in [46]. The multiscattering of neutron in a few cells can be considered as a veto. Owing the liquid nature of ^3He the dead volume between the cells can be so small as a microns copper foils of the walls between the cells. Consequently, the probability for neutron to escape after a single scattering can be minimized.

- A high transparency to γ -rays due to low Compton cross-section and the absence of photoelectric effect. No intrinsic X-rays.

- A high signal to noise ratio, due to the narrow energy integration range expected for a WIMP signal. Since the target nucleus ($m = 2.81 \text{ GeV}/c^2$) is much lighter than the incoming neutralino, the maximum recoil energy does only depend weakly on the WIMP mass. As a matter of fact, the recoil energy range needs to be studied only below 6 keV [10, 46].

- The target material being a quantum liquid, it has no coherent recoil unlike crystals and can be most easily recycled.

5 The current state: neutron, muon and low energy electron test of the superfluid ^3He bolometer

5.1 Neutrons

Neutrons were the first particles studied in superfluid ^3He [13] for their large energy release (17). Of particular interest was the study of the rapid and inhomogeneous phase transition of a small region around the neutron impact, for the possibility of topological defect creation in the superfluid in analogy with the Kibble mechanism in cosmology [40]. The neutrons, emitted by a moderated AmBe source, produce large signals in the bolometer. A deficit of about 120 keV with respect to the expected 764 keV is observed (figure 4); part of this deficit is accounted for by ultra-violet scintillation of the ^3He , the rest is interpreted in terms of energy trapped in the form of metastable topological defects of the superfluid (e. g. quantized vortices).

5.2 Muons

Cosmic muons are expected to deposit about 16 keV/mm in liquid ^3He at 0 bar. Muons represent thus bolometric events about an order of magnitude below neutrons. A muon test of the detector and its comparison to a numerical simulation by Geant4 in the frame of the MACHe3 collaboration yielded good agreement (figure 5), the 20-25 % difference between the experimental and the calculated detection spectra being due to ultra-violet scintillation [47]. Both peaks are smoothed through the geometrical averaging over all possible incidence angles.

Final evidence for the muonic nature of the observed energy peak at about 50~60 keV at ground level was brought by the recent experiment with a 3-cell prototype. The simultaneous detection in 3 adjacent cells allowed to discriminate with large efficiency the muons, who are, depending on their trajectory, generally detected coincidentally in two or more cells. This setup therefore allowed to demonstrate the large muon rejection efficiency of a future underground multicell detector.

5.3 Electrons

Since the energy range of a neutralino scattering is expected to be in the keV range, the proof that a 1 keV detection resolution and threshold could be attained had to be brought using a known particle source. A low activity ^{57}Co source was therefore implemented directly in one cell (cell B). Such a source emits γ -rays mainly at about 120 keV, which have a weak Compton scattering cross-section with the ^3He , but also low energy electrons

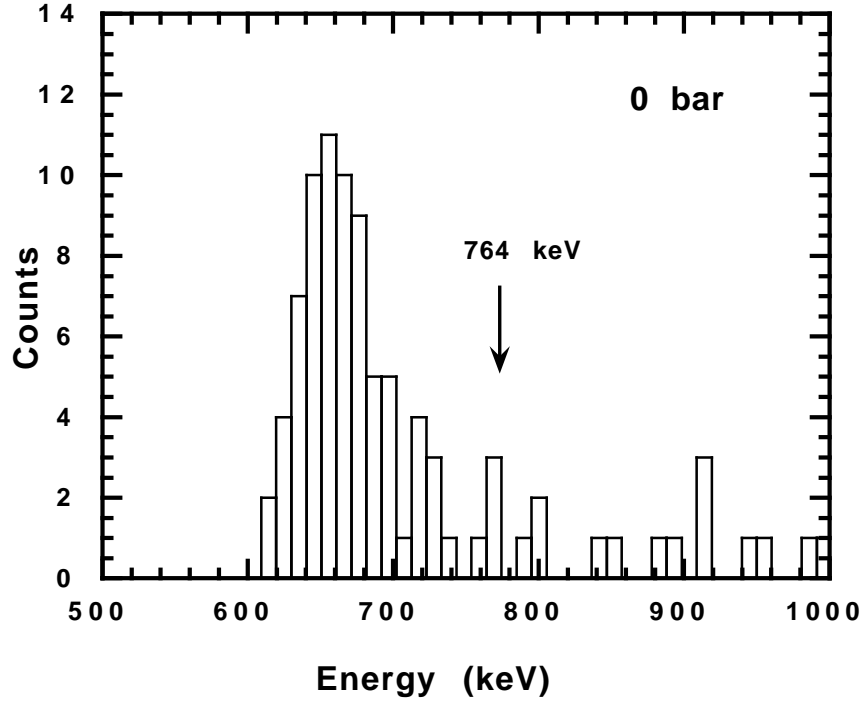


Figure 4: Detected energy spectrum associated to neutrons. An independent bolometric calibration of the cell allows to compare quantitatively the measured peak to the expected 764 keV, yielding a deficit of about 120 keV (see text).

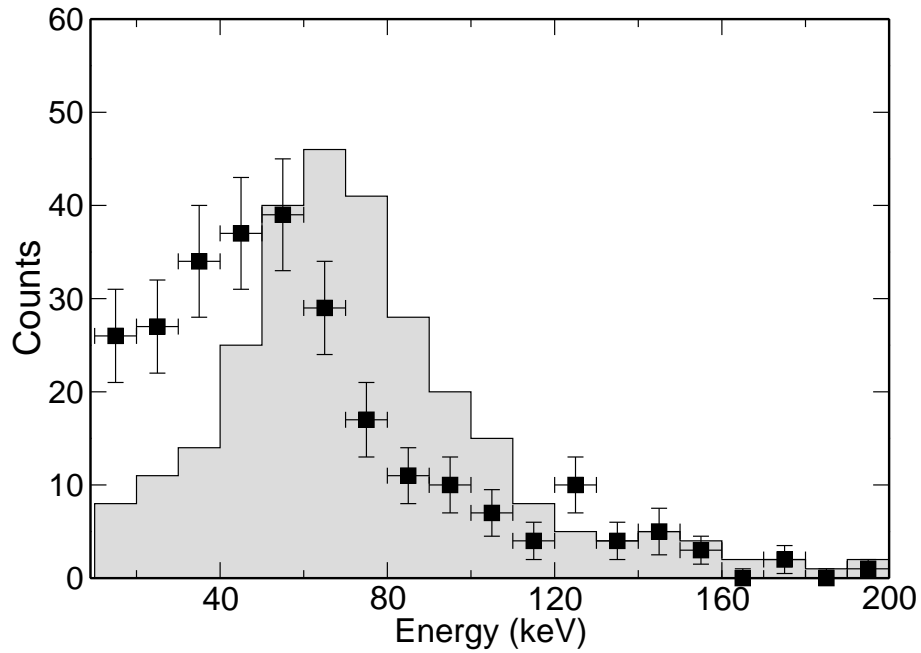


Figure 5: Cosmic muon detection spectrum, calculated (histogram) and experimental (points). The detection spectra qualitatively agree; the numerical simulation calculating the energy release of the muons without taking into account losses by ultra-violet scintillation, the difference of the maxima of about 25% allows to estimate the scintillation rate produced by ionizing events in superfluid ^3He .

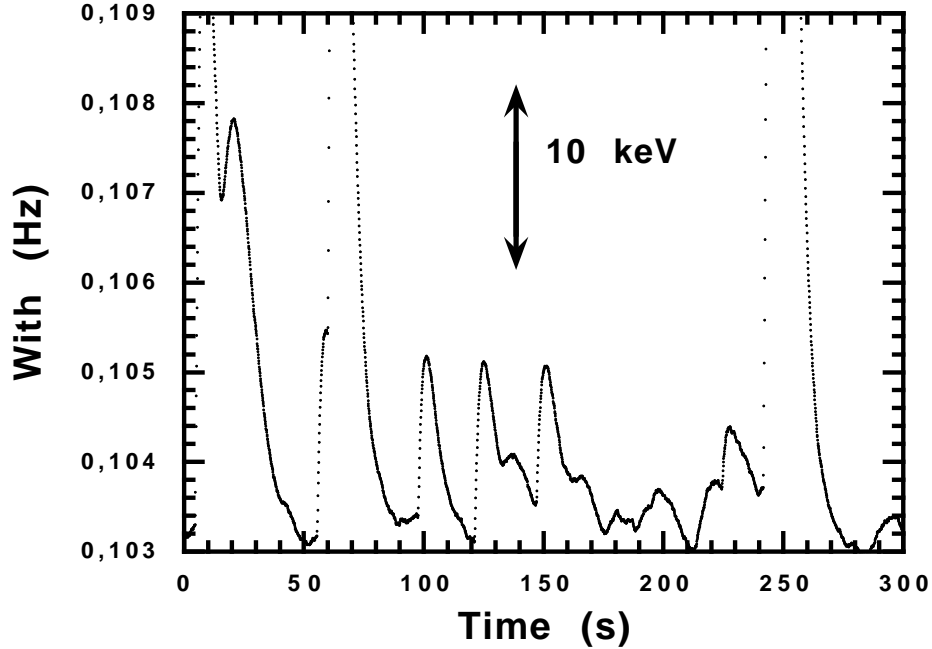


Figure 6: Detection of single electrons at keV level from the ^{57}Co source. Events at about 7 and 14 keV are easily detected. Even some unidentified bolometric events as small as 1 keV are clearly visible.

(from internal conversion and Auger effect) which thermalize completely in the liquid of cell B. Such low energy electron events are expected mainly at about 7 and 14 keV, and only in cell B [48, 49]. Measurements on the 3-cell prototype indeed allowed to identify such bolometric events, again an order of magnitude below typical muons (figure 6). The low energy detection spectrum in cell B and its comparison to cell A (without source) allows to clearly identify these events as produced by the ^{57}Co source (figure 7).

6 Discussion and outlook

The nature of cosmological dark matter involves physics, going beyond the Standard model of electroweak and strong interactions. Various candidates for dark matter follow from different arguments of particle theory and can co-exist in multicomponent dark matter scenarios. Discrimination of dark matter components inevitably involves combination of experimental methods and extension of such methods of dark matter search is important.

Recently possible set of dark matter candidates was enriched by idea of composite dark matter, which consists of atom-like systems of heavy electrically charged particles. These atom-like systems can have very small size and behave as weakly interacting particles. However, it turned out that realistic scenario of composite dark matter inevitably predicts existence of O-helium component (an "atom", in which heavy particle with charge -2 is bound with ^4He nucleus). This nuclear interacting component can be even dominant form of dark matter, but still remain elusive for the existing means of direct search for Weakly and Strongly Interacting Dark Matter Particles. New approach to cover the gap in experimental maintenance is needed to probe the existence of this exotic dark matter component.

^3He is a promising target material, though very young in the particle detection community. The bolometric experiment requires extremely low working temperatures and superfluid ^3He is all but a standard detector material for the search of non-baryonic Dark Matter. Since the original proposal of the use of ^3He for particle detection, the detection threshold and sensitivity have been improved by 2 orders of magnitude, reaching nowadays 1 keV, which is already the expected energy range for a neutralino impact. The use of a ^{57}Co source producing a well known γ -ray and low energy electron spectrum directly in one bolometric cell allowed to

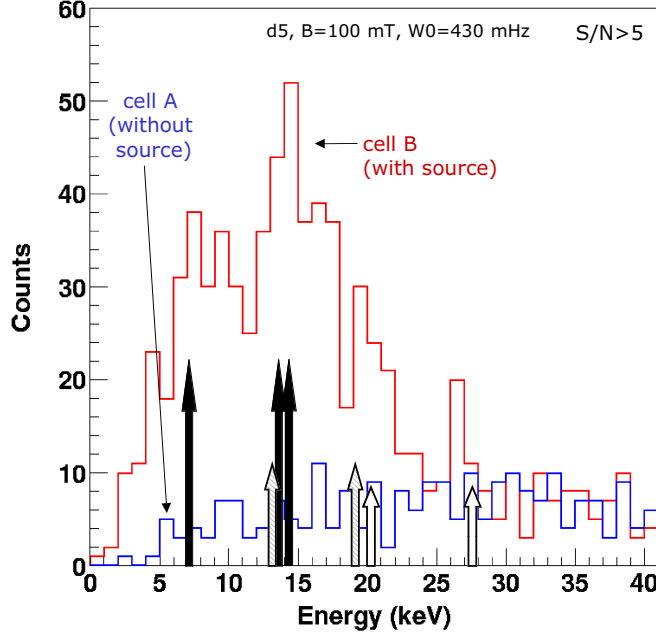


Figure 7: Detection spectrum in cell B (with source) at low energies. The observed spectrum coincides very well with the expected electron lines from the source (arrows). For comparison, the spectrum in cell A (without source) does not display any comparable structure (arrow shows the data from second cell). Note that the energy scale chosen takes into account the ultra-violet losses of about 25 % of ionising event.

illustrate both our understanding of the detector at keV level and the high transparency of the target material to γ -rays. In addition, the simultaneous detection in 3 adjacent cells demonstrated the future rejection efficiency versus ionizing events of a large multi-cell detector. Even the existing ground-based prototype can shed light on the possible existence of nuclear interacting DM component (O-helium) in a rather wide range of its parameters. Analysis of data from this prototype can provide complete test of composite dark matter models, being combined with future accelerator and cosmic ray searches for charged constituents of such forms of dark matter. The following mayor steps are planned to improve the ULTIMA experiment in the coming years:

In the absence of artificial laboratory sources, the detection signal is currently largely dominated by cosmic muons. The next steps will therefore necessarily lead the experiment to an underground laboratory with a muon flux reduced by 5 or 6 orders of magnitude.

Parallel methods of discrimination of ionizing events are in study. As in other materials, the fraction of energy emitted by the ^3He as ultra-violet scintillation can provide a fine criterium of discrimination. Alternative methods of thermometry to the classical VWR are currently thought of. Microfabricated silicon VWRs are already being produced and tested in Grenoble [50] and will allow to mass-fabricate the bolometric cells. In parallel, a method of thermometry based on Nuclear Magnetic Resonance (NMR) of the superfluid is currently being tested and may provide in the future a thermometric probe at $100\,\mu\text{K}$ with time constants below 1 ms.

The increase of the target mass to about 100 g should be possible in the coming years without demanding any extreme technological and cryogenical advance. As we have shown in the present paper such a target mass would already allow to test the current positive results of the DAMA experiment, sensitive to the spin-dependent

interaction [1]. Depending on the success of the experiment, a more challenging increase of the target mass to 1~10 kg may be thought of. Such a large detector using 10^3 independent bolometric cells would allow to look deep into the parameter space of possible Dark Matter models.

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